(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 February 2001 (01.02.2001)

PCT

(10) International Publication Number
WO 01/08169 A2

(51) International Patent Classification[7]: H01B 12/00

(21) International Application Number: PCT/US00/19208

(22) International Filing Date: 14 July 2000 (14.07.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

60/145,468	23 July 1999 (23.07.1999)	US
60/166,140	18 November 1999 (18.11.1999)	US
60/166,145	18 November 1999 (18.11.1999)	US
60/166,297	18 November 1999 (18.11.1999)	US
09/500,717	9 February 2000 (09.02.2000)	US
09/500,718	9 February 2000 (09.02.2000)	US
09/500,701	9 February 2000 (09.02.2000)	US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier applications:

US	60/145,468 (CON)
Filed on	23 July 1999 (23.07.1999)
US	60/166,140 (CON)
Filed on	18 November 1999 (18.11.1999)
US	60/166,145 (CON)
Filed on	18 November 1999 (18.11.1999)
US	60/166,297 (CON)
Filed on	18 November 1999 (18.11.1999)
US	09/500,701 (CON)
Filed on	9 February 2000 (09.02.2000)
US	09/500,717 (CON)
Filed on	9 February 2000 (09.02.2000)
US	09/500,718 (CON)
Filed on	9 February 2000 (09.02.2000)

(71) Applicant *(for all designated States except US)*: **AMERICAN SUPERCONDUCTOR CORPORATION** [US/US]; Two Technology Drive, Westborough, MA 01581-1727 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **MALOZEMOFF, Alexis, P.** [US/US]; 37 Walnut Street, Lexington, MA 02421 (US). **RILEY, Gilbert, N., Jr.** [US/US]; 630 Hemenway Street, Marlborough, MA 01752 (US). **SNITCHLER, Gregory, L.** [US/US]; 64 Ireta Road, Shrewsbury, MA 01545 (US). **OTTO, Alexander** [CA/US]; 92 Garrison Road, Chelmsford, MA 01824 (US). **BUCKLES, Warren, Elliot** [US/US]; 1217 Rutledge Street, Madison, WI 53703 (US). **LI, Qi** [US/US]; 12 Robert Road, Marlborough, MA 01752 (US).

(74) Agent: **HEIBEL, George, E.**; Fish & Richardson P.C., 45 Rockefeller Plaza, Suite 2800, New York, NY 10111 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

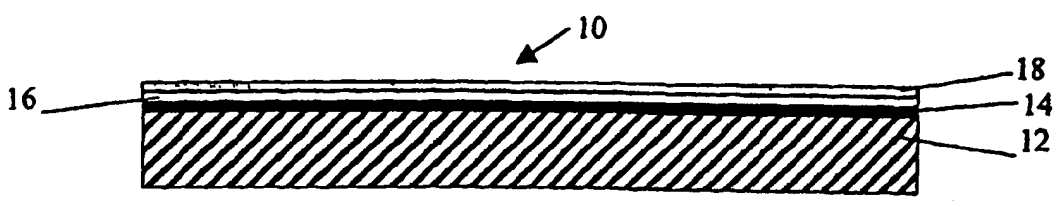
(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:

— *Without international search report and to be republished upon receipt of that report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: COATED CONDUCTORS WITH REDUCED A.C. LOSS



(57) Abstract: Coated conductors and methods of fabricating the same are provided, for minimizing a.c. losses during operation. Multilayered articles include multiple conductive layers in electronic communication through interlayer connections. Conductive paths are fabricated on the conductive layers and through interlayer connections between these layers so that current travels the length of the conductors with minimal a.c. losses.

WO 01/08169 A2

Coated Conductors with Reduced A.C. Loss

TECHNICAL FIELD

This invention relates to superconducting materials, and more particularly to articles fabricated from high temperature superconducting materials.

BACKGROUND

Coated conductors, comprising a single or multiple combinations of a biaxially textured high temperature superconductor ("HTS") layer on a thin buffer layer and a substrate tape, are a cost-performance-effective technology for manufacturing long length flexible HTS wire for magnet, coil and power applications. For example, these conductors should be useful for power transmission cables, rotor coils of motors and generators, and windings of transformers, as well as for magnets for medical magnetic resonance imaging (MRI), magnetic separation, ion-beam steering and magnetic levitation. Particularly of interest here are applications which use ac currents and fields, or fast ramps of current and field, for example ac power transmission cables, transformers, faultcurrent limiters, magnetic separation magnets, energy storage magnets, and high energy physics magnets.

Typically coated conductors come in the form of a tape several millimeters to a centimeter wide. The tape may include a single substrate coated with a biaxially textured buffer and epitaxial HTS layer, as in Fig. 1. Referring to Fig. 1, a representative coated conductor 10 of this type is shown, including a substrate 12, a biaxially textured buffer layer 14, and an epitaxial HTS layer 16. Layer 14 can be formed of any material capable of supporting layer 16. For example, layer 14 can be formed of a buffer layer material. Examples of buffer layer materials include metals and metal oxides, such as silver, nickel, TbO_x, GaO_x, CeO_2, yttria-stabilized zirconia (YSZ), Y_2O_3, $LaAlO_3$, $SrTiO_3$, $LaNiO_3$, Gd_2O_3, $LaCuO_3$, $SrRuO_3$, $NdGaO_3$, $NdAlO_3$ and nitrides as known in the art. A buffer material can be prepared using solution phase techniques, including metalorganic deposition, such as disclosed in, for example, S.S. Shoup et al., J. Am. Cer. Soc., vol. 81, 3019; D. Beach et al., Mat. Res. Soc. Symp. Proc., vol. 495, 263 (1988); M. Paranthaman et al., Superconductor Sci. Tech., vol. 12, 319 (1999); D.J. Lee et al., Japanese J. Appl. Phys., vol. 38, L178

(1999) and M.W. Rupich et al., I.E.E.E. Trans. on Appl. Supercon. vol. 9, 1527. Cap layer 18 is typically included.

Alternatively, the tape may include a single substrate coated on both sides with biaxially textured buffers and epitaxial HTS layers, as in Fig. 2, denoted as a "double sided" configuration. Referring to Fig. 2, a representative coated conductor 20 of this type is shown, including a substrate 22, biaxially textured buffer layers 24a and 24b and epitaxial HTS layers 26a and 26b. Cap layers 28a and 28b are typically included.

In alternating current (a.c.) current and field environments, it is generally important to minimize a.c. losses. Mechanisms of a.c. loss in superconducting wires have been extensively studied and are summarized, for example, in Martin Wilson, Superconducting Magnets, Chapter 8 (Clarendon Press, Oxford UK, 1983). An important contribution to the a.c. loss of superconducting wires is the so-called hysteretic loss, P_h, the size of which in watts per amp-meter can be estimated from the simple Bean formula given in Eq. 1,

$$P_h\ (W/Am) = fB_{peak}d \qquad \text{Eq. 1}$$

where f is the a.c. frequency, B_{peak} is the peak of the a.c. magnetic field acting on the conductor and d is the width of the superconducting strip perpendicular to the magnetic field. The requirements for low ac-loss vary from application to application, but for example in transformer applications, a goal of significantly less a.c. current loss than 1 mW/Am is desirable at power frequency (f = 50 or 60 Hz) in an a.c. magnetic field with B_{peak} = 0.1414 T (corresponding to the root mean square value of 0.1 T). In this case, Eq. 1 implies that the width d must be significantly less than 100 microns to achieve this goal. This width could be called the "critical hysteretic dimension" for remaining below the goal loss level. The critical hysteretic dimension differs for different applications requirements and different a.c. magnetic field

orientations and can be calculated by determining d in Eq. 1 from the known a.c. loss goal, a.c. frequency and a.c. magnetic field level.

When the a.c. magnetic field direction lies in the plane of simple single-layer coated conductor tapes exemplified in Fig. 1 (the "parallel" orientation), the perpendicular width d is small because it is simply the thickness of the HTS layer, which is usually less than about 10 microns, and so the a.c. loss is very low according to Eq. 1.

However, a major problem arises in the case that the a.c. magnetic field has significant components perpendicular to the tape plane (the "perpendicular" orientation). This situation can arise, for example, in conventional solenoidal coils at the ends of the coil. In this case the full tape width, several millimeters to a centimeter, comes into Eq. 1; this width is significantly greater than the typical critical hysteretic dimensions, which are on the order of 100 micron.

A first step toward a solution of this problem might be to pattern the superconducting strip into thinner strips, as shown in Fig. 3. Referring to Fig. 3, an overhead view of a HTS layer 25 is shown, in which the surface of the layer is divided into parallel conducting path strips 26 extending the length of the layer. Between the strips are insulating regions 27. However, if there is any conducting path between individual strips in this particular arrangement, those strips will be coupled together by induced currents. Additionally, the strips are typically connected together through the normal metal contacts or terminations at the ends of the conductor. In this case, additional loss mechanisms can arise through eddy currents in the non-superconducting connections ("coupling losses"), and, due to the terminations, the strips will still act as a single entity with respect to hysteretic losses, making the effective hysteretic dimension d in Eq. 1 equivalent to the full tape width, and consequently resulting in large ac losses.

The general solution to this problem, as described for example by Wilson, is as follows: the conducting strip needs not only to be broken up into finer strips with dimensions smaller than the critical hysteretic dimension, but also to be twisted and/or transposed with a sufficiently high transverse resistivity $\square_t$ between the filaments. In particular, to minimize the additional eddy current coupling losses, the pitch length of

the transposition L must be such as to minimize the quantity $L^2/\square_t$ (the specific numerical target can be determined from formulas in Wilson plus extensions to an aspected geometry, e.g. by K. Kwasnitsa et al., 4th European Conference on Applied Superconductivity, Sitges, Spain, Sept. 14-17, 1999).

Browne et al. disclosed a structure in which thin filaments of the low temperature superconductor Nb_3Sn, patterned into filaments parallel to the tape axis, were deposited helically around a cylindrical form to achieve a twisted and transposed configuration (U. S. Pat. No. 3,763,552, October 9, 1973). However, such a solution has a low packing density because of the space taken up by the cylindrical form.

In the context of HTS coated conductors, it would be desirable to provide methods and articles that overcome the shortcomings associated with the prior art.

SUMMARY OF THE INVENTION

This invention relates to practical superconducting conductors based upon biaxially textured high temperature superconductor (HTS) coatings (coated conductors). In particular, methods for producing articles, and articles produced in accordance therewith are described which provide reduced a.c. loss under a.c. fields, particularly with components oriented perpendicular to the tape plane.

The invention is based on the discovery that coated conductors can be fabricated in a way that minimizes losses incurred in alternating current applications. The conductors are fabricated with multiple conducting paths, each of which comprises path segments which extend across at least two conducting layers, and further extend between these layers.

The invention successfully achieves the transposition which is necessary for decoupling the individual filaments and reducing ac losses in the perpendicular ac field configuration.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present

invention, suitable methods and materials are described below. In case of conflict, the present specification, including definitions, will control. In addition, the materials, methods, and examples are illustrative only and not intended to be limiting.

Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustration of a side view of a prior art coated conductor tape structure in a "basic" configuration.

Fig. 2 is a schematic illustration of a side view of a prior art coated conductor tape structure in a "double sided" configuration.

Fig. 3 is a schematic illustration of an overhead view of a prior art coated conductor tape structure designed to pattern superconducting strips into thinner strips.

Fig. 4 is a schematic illustration of a perspective view of a particular conductive path for a "basic" coated conductor configuration according to a particular embodiment of the invention.

Fig. 5 is a schematic illustration of an overhead view of a patterned HTS layer according to a particular embodiment of the invention.

Fig. 6 is a schematic illustration of a side view of a coated conductor tape structure in a "face-to-face" configuration, according to a particular embodiment of the invention.

Fig. 7 is a schematic illustration of an overhead view of a patterned HTS layer according to a particular embodiment of the invention.

Fig. 7a is an end on view of the HTS layer of Fig. 7.

Fig. 8 is a schematic illustration of an overhead view of a multilayered coated conductor according to a particular embodiment of the invention.

Fig. 9 is a schematic illustration of an overhead view of a highly resistant layer according to a particular embodiment of the invention.

Fig. 10 is a schematic illustration of an overhead view of a patterned HTS layer according to a particular embodiment of the invention.

Fig. 10a is an end on view of the HTS layer of Fig. 10.

Fig. 11 is a schematic illustration of an overhead view of a coated conductor including a conducting tab according to a particular embodiment of the invention.

Fig. 12 is a schematic illustration of an overhead view of a coated conductor including bridge contacts according to a particular embodiment of the invention.

Dimensions of particular layers and features of the drawings are not necessarily to scale.

DETAILED DESCRIPTION

The invention is understood to apply to a variety of coated conductor configurations which yield a long tape with a layer or multiple layers of biaxially textured high temperature superconductor.

The substrate can be formed of alloys having one or more surfaces that are biaxially textured (e.g., (113)[211]) or cube textured (e.g., (100)[001] or (100)[011]). The alloys can have a relatively low Curie temperature (e.g., at most about 80K, at most about 40K, or at most about 20K).

In certain embodiments, the substrate is a binary alloy that contains two of the following metals: copper, nickel, chromium, vanadium, aluminum, silver, iron, palladium, molybdenum, gold and zinc. For example, a binary alloy can be formed of nickel and chromium (e.g., nickel and at most 20 atomic percent chromium, nickel and from about five to about 18 atomic percent chromium, or nickel and from about 10 to about 15 atomic percent chromium). As another example, a binary alloy can be formed of nickel and copper (e.g., copper and from about five to about 45 atomic percent nickel, copper and from about 10 to about 40 atomic percent nickel, or copper and from about 25 to about 35 atomic percent nickel). A binary alloy can further include relatively small amounts of impurities (e.g., less than about 0.1 atomic percent of impurities, less than about 0.01 atomic percent of impurities, or less than about 0.005 atomic percent of impurities).

In some embodiments, the substrate contains more than two metals (e.g., a ternary alloy or a quarternary alloy). In these embodiments the alloy can contain one or more oxide formers (e.g., Mg, Al, Ti, Cr, Ga, Ge, Zr, Hf, Y, Si, Pr, Eu, Gd, Tb, Dy,

Ho, Lu, Th, Er, Tm, Be, Ce, Nd, Sm, Yb and/or La, with Al being the preferred oxide former), as well as two of the following metals: copper, nickel, chromium, vanadium, aluminum, silver, iron, palladium, molybdenum, gold and zinc. The alloys can contain at least about 0.5 atomic percent oxide former (e.g., at least about one atomic percent oxide former, or at least about two atomic percent oxide former) and at most about 25 atomic percent oxide former (e.g., at most about 10 atomic percent oxide former, or at most about four atomic percent oxide former). For example, the alloy can include an oxide former (e.g., at least about 0.5 aluminum), from about 25 atomic percent to about 55 atomic percent nickel (e.g., from about 35 atomic percent to about 55 atomic percent nickel, or from about 40 atomic percent to about 55 atomic percent nickel) with the balance being copper. As another example, the alloy can include an oxide former (e.g., at least about 0.5 atomic aluminum), from about five atomic percent to about 20 atomic percent chromium (e.g., from about 10 atomic percent to about 18 atomic percent chromium, or from about 10 atomic percent to about 15 atomic percent chromium) with the balance being nickel. The alloys can include relatively small amounts of impurities (e.g., less than about 0.1 atomic percent of impurities, less than about 0.01 atomic percent of impurities, or less than about 0.005 atomic percent of impurities).

An alloy can be produced by, for example, combining the constituents in powder form, melting and cooling or, for example, by diffusing the powder constituents together in solid state. The alloy can then be formed by deformation texturing (e.g, annealing and rolling, swaging, extrusion and/or drawing) to form a textured surface (e.g., biaxially textured or cube textured). Alternatively, the alloy constituents can be stacked in a jelly roll configuration, and then deformation textured. In some embodiments, a material with a relatively low coefficient of thermal expansion (e.g, Nb, Mo, Ta, V, Cr, Zr, Pd, Sb, NbTi, an intermetallic such as NiAl or Ni_3Al, or mixtures thereof) can be formed into a rod and embedded into the alloy prior to deformation texturing.

These methods are described in commonly owned U.S. Patent Application No. 09/283,775, filed March 31, 1999, and entitled "Alloy Materials;" commonly owned U.S. Patent Application No. 09/283,777, filed March 31, 1999, and entitled "Alloy

Materials;" PCT Publication No. WO 99/17307, published on April 8, 1999, and entitled "Substrates with Improved Oxidation Resistance;" and PCT Publication No. WO 99/16941, published on April 8, 1999, and entitled "Substrates for Superconductors".

In some embodiments, a buffer layer can be formed using ion beam assisted deposition (IBAD). In this technique, a buffer layer material is evaporated using, for example, electron beam evaporation, sputtering deposition, or pulsed laser deposition while an ion beam (e.g., an argon ion beam) is directed at a smooth amorphous surface of a substrate onto which the evaporated buffer layer material is deposited.

For example, the buffer layer can be formed by ion beam assisted deposition by evaporating a buffer layer material having a rock-salt like structure (e.g., a material having a rock salt structure, such as an oxide, including MgO, or a nitride) onto a smooth, amorphous surface (e.g., a surface having a root mean square roughness of less than about 100 Angstroms) of a substrate so that the buffer layer material has a surface with substantial alignment (e.g., about 13° or less), both in-plane and out-of-plane.

The conditions used during deposition of the buffer layer material can include, for example, a substrate temperature of from about 0°C to about 400°C (e.g., from about room temperature to about 400°C), a deposition rate of from about 1.0 Angstrom per second to about 4.4 Angstroms per second, an ion energy of from about 200 eV to about 1200 eV, and/or an ion flux of from about 110 microamperes per square centimeter to about 120 microamperes per square centimeter.

In some embodiments, the substrate is formed of a material having a polycrystalline, non-amorphous base structure (e.g., a metal alloy, such as a nickel alloy) with a smooth amorphous surface formed of a different material (e.g., Si_3N_4).

In certain embodiments, a plurality of buffer layers can be deposited by epitaxial growth on an original IBAD surface. Each buffer layer can have substantial alignment (e.g., about 13° or less), both in-plane and out-of-plane.

These methods are described in PCT Publication No. WO 99/25908, published on May 27, 1999, and entitled "Thin Films Having A Rock-Salt-Like Structure Deposited on Amorphous Surfaces".

In some embodiments, stable oxide formation can be mitigated until a first epitaxial (for example, buffer) layer is formed on the biaxially textured alloy surface, using an intermediate layer disposed on the surface of the substrate. Intermediate layers suitable for use in the present invention include those epitaxial metal or alloy layers that do not form surface oxides when exposed to conditions as established by P_{O2} and temperature required for the initial growth of epitaxial buffer layer films. In addition, the buffer layer acts as a barrier to prevent substrate element(s) from migrating to the surface of the intermediate layer and forming oxides during the initial growth of the epitaxial layer. Absent such an intermediate layer, one or more elements in the substrate would be expected to form thermodynamically stable oxide(s) at the substrate surface which could significantly impede the deposition of epitaxial layers due to, for example, lack of texture in this oxide layer.

In some embodiments, the intermediate layer is transient in nature. "Transient," as used herein, refers to an intermediate layer that is wholly or partly incorporated into or with the biaxially textured substrate following the initial nucleation and growth of the epitaxial film. Even under these circumstances, the intermediate layer and biaxially textured substrate remain distinct until the epitaxial nature of the deposited film has been established. The use of transient intermediate layers may be preferred when the intermediate layer possesses some undesirable property, for example, the intermediate layer is magnetic, such as nickel.

Exemplary intermediate metal layers include nickel, gold, silver, palladium, and alloys thereof. Impurities or alloys may include alloys of nickel and/or copper. Epitaxial films or layers deposited on an intermediate layer can include metal oxides, chalcogenides, halides, and nitrides. In preferred embodiments, the intermediate metal layer does not oxidize under epitaxial film deposition conditions.

Care should be taken that the deposited intermediate layer is not completely incorporated into or does not completely diffuse into the substrate before nucleation and growth of the initial buffer layer structure causes the epitaxial layer to be established. This means that after selecting the metal (or alloy) for proper attributes such as diffusion constant in the substrate alloy, thermodynamic stability against oxidation under practical epitaxial buffer layer growth conditions and lattice matching

with the epitaxial layer, the thickness of the deposited metal layer has to be adapted to the epitaxial layer deposition conditions, in particular to temperature.

Deposition of the intermediate metal layer can be done in a vacuum process such as evaporation or sputtering, or by electro-chemical means such as electroplating (with or without electrodes). These deposited intermediate metal layers may or may not be epitaxial after deposition (depending on substrate temperature during deposition), but epitaxial orientation can subsequently be obtained during a post-deposition heat treatment.

In certain embodiments, the formation of oxide buffer layers can be carried out so as to promote wetting of an underlying substrate layer. Additionally, in particular embodiments, the formation of metal oxide layers can be carried out using metal alkoxide precursors (for example, "sol gel" precursors), in which the level of carbon contamination can be greatly reduced over other known processes using metal alkoxide precursors.

In certain embodiments, solution coating processes can be used for deposition of one or a combination of any of the oxide layers on textured substrates; however, they can be particularly applicable for deposition of the initial (seed) layer on a textured metal substrate. The role of the seed layer is to provide 1) protection of the substrate from oxidation during deposition of the next oxide layer when carried out in an oxidizing atmosphere relative to the substrate (for example, magnetron sputter deposition of yttria-stabilized zirconia from an oxide target); and 2) an epitaxial template for growth of subsequent oxide layers. In order to meet these requirements, the seed layer should grow epitaxially over the entire surface of the metal substrate and be free of any contaminants that may interfere with the deposition of subsequent epitaxial oxide layers.

The formation of oxide buffer layers can be carried out so as to promote wetting of an underlying substrate layer. Additionally, in particular embodiments, the formation of metal oxide layers can be carried out using metal alkoxide precursors (for example, "sol gel" precursors), in which the level of carbon contamination can be greatly reduced over other known processes using metal alkoxide precursors.

This heating step can be carried out after, or concurrently with, the drying of excess solvent from the sol gel precursor film. It must be carried out prior to decomposition of the precursor film, however.

The carbon contamination accompanying conventional oxide film preparation in a reducing environment (e.g., 4%H_2-Ar) is believed to be the result of an incomplete removal of the organic components of the precursor film. The presence of carbon-containing contaminants C_xH_y and $C_aH_bO_c$ in or near the oxide layer can be detrimental, since they can alter the epitaxial deposition of subsequent oxide layers. Additionally, it is likely that the trapped carbon-containing contaminants buried in the film can be oxidized during the processing steps for subsequent oxide layers, which can utilize oxidizing atmospheres. The oxidation of the carbon-containing contaminants can result in CO_2 formation, and the subsequent blistering of the film, and possible delamination of the film, or other defects in the composite structure. Thus, it is undesirable to allow carbon-containing contaminants arising from metal alkoxide decomposition to become oxidized only after the oxide layer is formed. Preferably, the carbon-containing contaminants are oxidized (and hence removed from the film structure as CO_2) as the decomposition occurs. Also the presence of carbon-containing species on or near film surfaces can inhibit the epitaxial growth of subsequent oxide layers.

According to particular embodiments, after coating a metal substrate or buffer layer, the precursor solution can be air dried, and then heated in an initial decomposition step. Alternatively, the precursor solution can be directly heated in an initial decomposition step, under an atmosphere that is reducing relative to the metal substrate. Once the oxide layer initially nucleates on the metal substrate in the desired epitaxial orientation, the oxygen level of the process gas is increased, for example, by adding water vapor or oxygen. The nucleation step requires from about 5 minutes to about 30 minutes to take place under typical conditions.

These methods are described in U.S. Patent Application Serial No. _____, filed on even date herewith, and entitled "Enhanced Purity Oxide Layer Formation".

In certain embodiments, an epitaxial buffer layer can be formed using a low vacuum vapor deposition process (e.g., a process performed at a pressure of at least about $1x10^{-3}$ Torr). The process can include forming the epitaxial layer using a relatively high velocity and/or focused gas beam of buffer layer material.

The buffer layer material in the gas beam can have a velocity of greater than about one meter per second (e.g., greater than about 10 meters per second or greater than about 100 meters per second). At least about 50% of the buffer layer material in the beam can be incident on the target surface (e.g., at least about 75% of the buffer layer material in the beam can be incident on the target surface, or at least about 90% of the buffer layer material in the beam can be incident on the target surface).

The method can include placing a target surface (e.g., a substrate surface or a buffer layer surface) in a low vacuum environment, and heating the target surface to a temperature which is greater than the threshold temperature for forming an epitaxial layer of the desired material on the target surface in a high vacuum environment (e.g., less than about $1x10^{-3}$ Torr, such as less than about $1x10^{-4}$ Torr) under otherwise identical conditions. A gas beam containing the buffer layer material and optionally an inert carrier gas is directed at the target surface at a velocity of at least about one meter per second. A conditioning gas is provided in the low vacuum environment. The conditioning gas can be contained in the gas beam, or the conditioning gas can be introduced into the low vacuum environment in a different manner (e.g., leaked into the environment). The conditioning gas can react with species (e.g., contaminants) present at the target surface to remove the species, which can promote the nucleation of the epitaxial buffer layer.

The epitaxial buffer layer can be grown on a target surface using a low vacuum (e.g., at least about $1x10^{-3}$ Torr, at least about 0.1 Torr, or at least about 1 Torr) at a surface temperature below the temperature used to grow the epitaxial layer using physical vapor deposition at a high vacuum (e.g., at most about $1x10^{-4}$ Torr). The temperature of the target surface can be, for example, from about 25°C to about 800°C (e.g., from about 500°C to about 800°C, or from about 500°C to about 650°C).

The epitaxial layer can be grown at a relatively fast rate, such as, for example, at least about 50 Angstroms per second.

These methods are described in U.S. Patent No. 6,027,564, issued February 22, 2000, and entitled "Low Vacuum Process for Producing Epitaxial Layers;" U.S. Patent No. 6,022, 832, issued February 8, 2000, and entitled "Low Vacuum Process for Producing Superconductor Articles with Epitaxial Layers;" and/or commonly owned U.S. Patent Application No. 09/007,372, filed January 15, 1998, and entitled "Low Vacuum Process for Producing Epitaxial Layers of Semiconductor Material".

In some embodiments, an epitaxial buffer layer can be deposited by sputtering from a metal or metal oxide target at a high throughput. Heating of the substrate can be accomplished by resistive heating or bias and electric potential to obtain an epitaxial morphology. A deposition dwell may be used to form an oxide epitaxial film from a metal or metal oxide target.

The oxide layer typically present on substrates can be removed by exposure of the substrate surface to energetic ions within a reducing environment, also known as Ion Beam etching. Ion Beam etching can be used to clean the substrate prior to film deposition, by removing residual oxide or impurities from the substrate, and producing an essentially oxide-free preferably biaxially textured substrate surface. This improves the contact between the substrate and subsequently deposited material. Energetic ions can be produced by various ion guns, for example, which accelerate ions such as Ar^+ toward a substrate surface. Preferably, gridded ion sources with beam voltages greater than 150 ev are utilized. Alternatively, a plasma can be established in a region near the substrate surface. Within this region, ions chemically interact with a substrate surface to remove material from that surface, including metal oxides, to produce substantially oxide-free metal surface.

Another method to remove oxide layers from a substrate is to electrically bias the substrate. If the substrate tape or wire is made negative with respect to the anode potential, it will be subjected to a steady bombardment by ions from the gas prior to the deposition (if the target is shuttered) or during the entire film deposition. This ion bombardment can clean the wire or tape surface of absorbed gases that might otherwise be incorporated in the film and also heat the substrate to elevated deposition temperatures. Such ion bombardment can be further advantageous by improving the density or smoothness of the epitaxial film.

Upon formation of an appropriately textured, substantially oxide-free substrate surface, deposition of a buffer layer can begin. One or more buffer layers, each including a single metal or oxide layer, can be used. In some preferred embodiments, the substrate is allowed to pass through an apparatus adapted to carry out steps of the deposition method of these embodiments. For example, if the substrate is in the form of a wire or tape, the substrate can be passed linearly from a payout reel to a take-up reel, and steps can be performed on the substrate as it passes between the reels.

According to some embodiments, substrate materials are heated to elevated temperatures which are less than about 90% of the melting point of the substrate material but greater than the threshold temperature for forming an epitaxial layer of the desired material on the substrate material in a vacuum environment at the predetermined deposition rate. In order to form the appropriate buffer layer crystal structure and buffer layer smoothness, high substrate temperatures are generally preferred. Typical lower limit temperatures for the growth of oxide layers on metal are approximately 200°C to 800°C, preferably 500°C to 800°C, and more preferably, 650°C to 800°C. Various well-known methods such as radiative heating, convection heating, and conduction heating are suitable for short (2 cm to 10 cm) lengths of substrate, but for longer (1m to 100 m) lengths, these techniques may not be well suited. Also to obtain desired high throughput rates in a manufacturing process, the substrate wire or tape must be moving or transferring between deposition stations during the process. According to particular embodiments, the substrates are heated by resistive heating, that is, by passing a current through the metal substrate, which is easily scaleable to long length manufacturing processes. This approach works well while instantaneously allowing for rapid travel between these zones. Temperature control can be accomplished by using optical pyrometers and closed loop feedback systems to control the power supplied to the substrate being heated. Current can be supplied to the substrate by electrodes which contact the substrate in at least two different segments of the substrate. For example, if the substrate, in the form of a tape or wire, is passed between reels, the reels themselves could act as electrodes. Alternatively, if guides are employed to transfer the substrate between reels, the guides could act as electrodes. The electrodes could also be completely independent

of any guides or reels as well. In some preferred embodiments, current is applied to the tape between current wheels.

In order that the deposition is carried out on tape that is at the appropriate temperature, the metal or oxide material that is deposited onto the tape is desirably deposited in a region between the current wheels. Because the current wheels can be efficient heat sinks and can thus cool the tape in regions proximate to the wheels, material is desirably not deposited in regions proximate to the wheels. In the case of sputtering, the charged material deposited onto the tape is desirably not influenced by other charged surfaces or materials proximate to the sputter flux path. For this reason, the sputter chamber is preferably configured to place components and surfaces which could influence or deflect the sputter flux, including chamber walls, and other deposition elements, in locations distant from the deposition zone so that they do not alter the desired linear flux path and deposition of metal or metal oxide in regions of the tape at the proper deposition temperature.

More details are provided in commonly owned United States Patent Application Serial No. 09/500,701, filed on February 9, 2000, and entitled "Oxide Layer Method," and commonly owned United States Patent Application Serial No. _____, filed on even date herewith, and entitled "Oxide Layer Method".

In preferred embodiments, three buffer layers are used. A layer of Y_2O_3 or CeO_2 (e.g., from about 20 nanometers to about 50 nanometers thick) is deposited (e.g., using electron beam evaporation) onto the substrate surface. A layer of YSZ (e.g., from about 0.2 micron to about 1 micron thick, such as about 0.5 micron thick) is deposited onto the surface of the Y_2O_3 or CeO_2 layer using sputtering (e.g, using magnetron sputtering). A CeO_2 layer (e.g., about 20 nanometers thick) is deposited (e.g, using magnetron sputttering) onto the YSZ surface. The surface of one or more of these layers can be chemically and/or thermally conditioned as described herein.

In certain embodiments, the underlying layer (e.g., a buffer layer or a different superconductor layer) can be conditioned (e.g., thermally conditioned and/or chemically conditioned) so that the superconductor layer is formed on a conditioned surface. The conditioned surface of the underlying layer can be biaxially textured (e.g., (113)[211]) or cube textured (e.g., (100)[011] or (100)[011]), have peaks in an

X-ray diffraction pole figure that have a full width at half maximum of less than about 20° (e.g., less than about 15°, less than about 10°, or from about 5° to about 10°), be smoother than before conditioning as determined by high resolution scanning electron microscopy or atomic force microscopy, have a relatively high density, have a relatively low density of impurities, exhibit enhanced adhesion to other material layers (e.g., a superconductor layer or a buffer layer) and/or exhibit a relatively small rocking curve width as measured by x-ray diffraction.

"Chemical conditioning" as used herein refers to a process which uses one or more chemical species (e.g., gas phase chemical species and/or solution phase chemical species) to affect changes in the surface of a material layer, such as a buffer layer or a superconductor material layer, so that the resulting surface exhibits one or more of the above noted properties.

"Thermal conditioning" as used herein refers to a process which uses elevated temperature with or without chemical conditioning to affect changes in the surface of a material layer, such as a buffer layer or a superconductor material layer, so that the resulting surface exhibits one or more of the above noted properties. Preferably, thermal conditioning occurs in a controlled environment (e.g., controlled gas pressure, controlled gas environment and/or controlled temperature).

Thermal conditioning can include heating the surface of the underlying layer to a temperature at least about 5°C above the deposition temperature or the crystallization temperature of the underlying layer (e.g., from about 15°C to about 500°C above the deposition temperature or the crystallization temperature of the underlying layer, from about 75°C to about 300°C above the deposition temperature or the crystallization temperature of the underlying layer, or from about 150°C to about 300°C above the deposition temperature or the crystallization temperature of the underlying layer). Examples of such temperatures are from about 500°C to about 1200°C (e.g., from about 800°C to about 1050°C). Thermal conditioning can be performed under a variety of pressure conditions, such as above atmospheric pressure, below atmospheric pressure, or at atmospheric pressure. Thermal conditioning can also be performed using a variety of gas environments (e.g., an oxidizing gas environment, a reducing gas environment, or an inert gas environment).

"Deposition temperature" as used herein refers to the temperature at which the layer being conditioned was deposited.

"Crystallization temperature" as used herein refers to the temperature at which a layer of material (e.g., the underlying layer) takes on a crystalline form.

Chemical conditioning can include vacuum techniques (e.g., reactive ion etching, plasma etching and/or etching with fluorine compounds, such as BF_3 and/or CF_4). Chemical conditioning techniques are disclosed, for example, in Silicon Processing for the VLSI Era, Vol. 1, eds. S. Wolf and R.N. Tanber, pp. 539-574, Lattice Press, Sunset Park, CA, 1986.

Alternatively or additionally, chemical conditioning can involve solution phase techniques, such as disclosed in Metallurgy and Metallurgical Engineering Series, 3d ed., George L. Kehl, McGraw-Hill, 1949. Such techniques can include contacting the surface of the underlying layer with a relatively mild acid solution (e.g., an acid solution containing less about 10 percent acid, less than about two percent acid, or less than about one percent acid). Examples of mild acid solutions include perchloric acid, nitric acid, hydrofluoric acid, hydrochloric acid, acetic acid and buffered acid solutions. In one embodiment, the mild acid solution is about one percent aqueous nitric acid. In certain embodiments, bromide-containing and/or bromine-containing compositions (e.g., a liquid bromine solution) can be used to condition the surface of a buffer layer or a superconductor layer.

This method can be used to form multiple buffer layers (e.g., two, three, four, or more buffer layers), with one or more of the buffer layers having a conditioned surface.

The method can also be used to form multiple superconductor layers, with one or more of the superconductor layers having a conditioned surface. For example, a superconductor layer can be formed and then thermally and/or chemically conditioned as described above. An additional superconductor layer can then be formed on the conditioned surface of the first superconductor layer. This process can be repeated as many times as desired.

These methods are described in commonly owned U.S. Provisional Patent Application No. 60/166, 140, filed November 18, 1999, and entitled "Multi-Layer

Articles and Methods of Making Same," and commonly owned U.S. Patent Application Serial No. _____, filed on even date herewith, and entitled "Multi-layer Articles and Methods of Making Same".

In certain embodiments, the superconductor layer can be formed from a precursor composition that has a relatively small amount of free acid. In aqueous solutions, this can correspond to a precursor composition with a relatively neutral pH (e.g., neither strongly acidic nor strongly basic). The precursor composition can be used to prepare multi-layer superconductors using a wide variety of materials which can be used as the underlying layer on which the superconductor layer is formed.

The total free acid concentration of the precursor composition can be less than about $1x10^{-3}$ molar (e.g., less than about $1x10^{-5}$ molar or about $1x10^{-7}$ molar). Examples of free acids that can be contained in a precursor composition include trifluoroacetic acid, acetic acid, nitric acid, sulfuric acid, acids of iodides, acids of bromides and acids of sulfates.

When the precursor composition contains water, the precursor composition can have a pH of at least about 3 (e.g., at least about 5 or about 7).

In some embodiments, the precursor composition can have a relatively low water content (e.g., less than about 50 volume percent water, less than about 35 volume percent water, less than about 25 volume percent water).

In embodiments in which the precursor composition contains trifluoroacetic acid and an alkaline earth metal (e.g., barium), the total amount of trifluoroacetic acid can be selected so that the mole ratio of fluorine contained in the precursor composition (e.g., in the form of trifluoroacetate) to the alkaline earth metal (e.g., barium ions) contained in the precursor composition is at least about 2:1 (e.g., from about 2:1 to about 18.5:1, or from about 2:1 to about 10:1).

Superconducting articles formed from such precursor compositions can include more than one superconductor layer (e.g., two superconductor layers disposed on each other). The combined thickness of the superconductor layers can be at least about one micron (e.g., at least about two microns, at least about three microns, at least about four microns, at least about five microns, or at least about six microns). The combined critical current density of the superconductor layers can be at least

about $5x10^5$ Amperes per square centimeter (e.g., at least about $1x10^6$ Amperes per square centimeter, or at least about $2x10^6$ Amperes per square centimeter).

In general, the precursor compositions can be prepared by combining soluble compounds of a first metal (e.g., copper), a second metal (e.g., an alkaline earth metal), and a rare earth metal with one or more desired solvents and optionally water. As used herein, "soluble compounds" of the first, second and rare earth metals refer to compounds of these metals that are capable of dissolving in the solvent(s) contained in the precursor compositions. Such compounds include, for example, salts (e.g., nitrates, acetates, alkoxides, iodides, sulfates and trifluoroacetates), oxides and hydroxides of these metals.

These methods and compositions are described in commonly owned U.S. Provisional Patent Application Serial No. 60/166, 297, filed on November 18, 1999, and entitled "Superconductor Articles and Compositions and Methods for Making Same," and commonly owned U.S. Patent Application No. _____, filed on even date herewith, and entitled "Superconductor Articles and Compositions and Methods for Making Same".

In certain embodiments, a precursor solution is formed of an organic solution containing metal trifluoroacetates prepared from powders of $BaCO_3$, $YCO_3 \cdot 3H_2O$ and $Cu(OH)_2CO_3$ combined and reacted using methods known to those skilled in the art. For example, the powders can be combined in a 2:1:3 ratio with between 20-30% (5.5-6.0 M) excess trifluoroacetic acid in methyl alcohol and then refluxed (e.g., for approximately four to ten hours) to produce a solution substantially 0.94 M based on copper content.

The precursor solution is then applied to a surface (e.g., a buffer layer surface), such as by spin coating or other techniques known to those skilled in the art.

After application to the surface (e.g, the buffer layer surface), the precursor solution is heat treated. Generally, the solution is heated at a rate of from about 0.5°C per minute to about 10°C per minute in moist oxygen (e.g., having a dew point in the range of from about 20°C to about 75°C) to a temperature in the range of from about 300°C to about 500°C. The coating is then heated for about one hour to a temperature of less than about 860°C (e.g., less than about 810°C) in a moist reducing nitrogen-

oxygen gas mixture (e.g., having a composition including from about 0.5% to about 5% oxygen). Optionally, the coating can be further heated to a temperature of from about 860°C to about 950°C for from about five to about 25 minutes. The coating is subsequently heated to a temperature of from about 400°C to about 500°C for at least about eight hours at in dry oxygen. The coating can then be cooled to room temperature in static dry oxygen.

These methods are described in U.S. Patent No. 5,231,074, issued on July 27, 1993, and entitled "Preparation of Highly Textured Oxide Superconducting Films from MOD Precursor Solutions".

In some embodiments, a metal oxyfluoride is deposited using one or more standard techniques, such as metalorganic solution deposition, metalorganic chemical vapor deposition, reactive evaporation, plasma spray, molecular beam epitaxy, laser ablation, ion beam sputtering, electron beam evaporation, depositing a metal trifluoroacetate coating and decomposing the coating as described herein. Multiple layers of metal oxyfluoride may be deposited.

Other constituent metallic elements of the desired oxide superconductor are also deposited in substantially stoichiometric proportions.

The metal oxyfluoride is converted into an oxide superconductor at a rate of conversion selected by adjusting temperature, vapor pressure of gaseous water or both. For example, the metal oxyfluoride can be converted in a processing gas having a moisture content of less than 100% relative humidity (e.g., less than about 95% relative humidity, less than about 50% relative humidity, or less than about 3% relative humidity) at 25°C to form some oxide superconductor, then completing the conversion using a processing gas having a higher moisture content (e.g., from about 95% relative humidity to about 100% relative humidity at 25°C). The temperature for converting the metal oxyfluoride can be in the range of from about 700°C to about 900°C (e.g., from about 700°C to about 835°C). The processing gas preferably contains from about 1 volume percent oxygen gas to about 10 volume percent oxygen gas.

These methods are described in PCT Publication No. WO 98/58415, published on December 23, 1998, and entitled "Controlled Conversion of Metal Oxyfluorides into Superconducting Oxides".

In certain embodiments, the preparation of the superconductor layer includes using a precursor composition containing a trifluoroacetate salt of one or more metals and a controlled total water content (e.g., controlled content of liquid water in the precursor composition and controlled content of water vapor in the surrounding environment) present when treating the precursor composition to form an intermediate of the superconductor layer (e.g., a metal oxyfluoride intermediate of the superconductor layer). For example, the precursor composition can have a relatively low water content (e.g., less than about 50 volume percent water, less than about 35 volume percent water, or less than about 25 volume percent water) and/or a relatively high solids content, whereas the surrounding gas environment can have a relatively high vapor pressure of water (e.g., from about 5 Torr to about 50 Torr water, from about 5 Torr to about 30 Torr water, or from about 10 Torr to about 25 Torr water). The superconductor layer intermediate (e.g., metal oxyfluoride intermediate) can be formed in a relatively short period of time (e.g., less than about five hours, less than about three hours, or less than about one hour).

Treating the precursor composition can include heating the precursor composition from an initial temperature (e.g., room temperature) to a temperature of from about 190°C to about 215°C (e.g., about 210°C) at a rate of at least about 5°C per minute (e.g., at least about 8°C per minute, or at least about 10°C per minute) in a water vapor pressure of from about 5 Torr to about 50 Torr water vapor (e.g., from about 5 Torr to about 30 Torr water vapor, or from about 10 Torr to about 25 Torr water vapor) . The nominal partial pressure of oxygen can be, for example, from about 0.1 Torr to about 760 Torr.

Heating is then continued to a temperature of from about 220°C to about 290°C (e.g., about 220°C) at a rate of from about 0.05°C per minute to about 0.4°C per minute (e.g., from about 0.1°C per minute to about 0.4°C per minute) in a water vapor pressure of from about 5 Torr to about 50 Torr water vapor (e.g., from about 5 Torr to about 30 Torr water vapor, or from about 10 Torr to about 25 Torr water

vapor). The nominal partial pressure of oxygen can be, for example, from about 0.1 Torr to about 760 Torr.

This is followed by heating to about 400°C at a rate of at least about 2°C per minute (e.g., at least about 3°C per minute, or at least about 5°C per minute) in a water vapor pressure of from about 5 Torr to about 50 Torr water vapor (e.g., from about 5 Torr to about 30 Torr water vapor, or from about 10 Torr to about 25 Torr water vapor) to form an intermediate of the superconductor material (e.g., a metal oxyfluoride intermediate). The nominal partial pressure of oxygen can be, for example, from about 0.1 Torr to about 760 Torr.

The intermediate can be heated to form the desired superconductor layer. For example, the intermediate can be heated to a temperature of from about 700°C to about 825°C in an environment containing from about 0.1 Torr to about 50 Torr oxygen and from about 0.1 Torr to about 150 Torr water vapor (e.g., about 12 Torr water vapor) with the balance being, for example, nitrogen and/or argon.

The method can result in a well-ordered superconductor layer (e.g., biaxially textured or cube textured) having a relatively high critical current density (e.g., at least about $5x10^5$ Amperes per square centimeter).

These methods are described in commonly owned U.S. Provisional Patent Application Serial No. 60/166,145, filed on November 18, 1999, and entitled "Methods and Compositions for Making a Multi-Layer Article," and commonly owned U.S. Patent Application No. _____, filed on even date herewith, and entitled "Methods and Compositions for Making a Multi-layer Article".

In certain embodiments, a metal oxyfluoride intermediate of a superconductor material can be prepared using a process that involves relatively few temperature ramps (e.g., less than three ramps, such as two ramps).

Alternatively or additionally, forming the metal oxyfluoride can include one or more steps in which the temperature is held substantially constant (e.g., constant within about 10°C, within about 5°C, within about 2°C, within about 1°C) for a relatively long period of time (e.g., more than about one minute, more than about five minutes, more than about 30 minutes, more than about an hour, more than about two hours, more than about four hours) after a first temperature ramp to a temperature

greater than about room temperature (e.g., at least about 50°C, at least about 100°C, at least about 200°C, at least about 215°C, from about 215°C to about 225°C, about 220°C).

Formation of the metal oxyfluoride intermediate can involve using more than one gas environment (e.g., a gas environment having a relatively high water vapor pressure and a gas environment having a relatively low water vapor pressure) while maintaining the temperature substantially constant (e.g., constant within about 10°C, within about 5°C, within about 2°C, within about 1°C) for a relatively long period of time (e.g., more than about one minute, more than about five minutes, more than about 30 minutes, more than about an hour, more than about two hours, more than about four hours). As an example, in a high water vapor pressure environment, the water vapor pressure can be from about 17 Torr to about 40 Torr (e.g., from about 25 Torr to about 38 Torr, such as about 32 Torr). A low water vapor pressure environment can have a water vapor pressure of less than about 1 Torr (e.g., less than about 0.1 Torr, less than about 10 milliTorr, about five milliTorr).

Generally, the metal oxyfluoride is formed by disposing a composition (e.g., a precursor solution) on a surface (e.g., a substrate surface, a buffer layer surface or a superconductor layer surface) and heating the composition. The methods of disposing the composition on the surface include spin coating, dip coating, web coating and other techniques known in the art.

Typically, in an initial decomposition step, the initial temperature in this step is about room temperature, and the final temperature is from about 215□C to about 225°C using a temperature ramp of 10□C per minute or less. During this step, the partial pressure of water vapor in the nominal gas environment is preferably maintained at from about 17 Torr to about 40 Torr. The partial pressure of oxygen in the nominal gas environment can be maintained at from about 0.1 Torr to about 760 Torr. The temperature and nominal gas environment are then held substantially constant for a relatively long period of time.

After this time period, the gas environment is changed to a relatively dry gas environment (e.g., less than about one Torr water vapor, less than about 0.1 Torr water vapor, less than about 10 milliTorr water vapor, five milliTorr water vapor)

while maintaining the temperature substantially constant. The temperature and nominal gas environment are then held substantially constant for a relatively long period of time.

After this time period, the nominal gas environment is maintained substantially constant and heating is continued to a temperature sufficient to form the metal oxyfluoride intermediate (e.g., about 400□C). This step is preferably performed using a temperature ramp of 10□C per minute or less.

The metal oxyfluoride intermediate can then be heated to form the desired superconductor layer. Typically, this step is performed by heating to a temperature of from about 700□C to about 825□C. During this step, the nominal gas environment typically can contain from about 0.1 Torr to about 50 Torr oxygen and from about 0.1 Torr to about 150 Torr (e.g., about 12 Torr) of water vapor with the balance being nitrogen and/or argon.

Preferably, the metal oxyfluoride intermediate has a relatively low defect density.

These methods are described in commonly owned U.S. Patent Application Serial No. _____, filed on even date herewith, and entitled "Methods of Making A Superconductor".

In certain embodiments, the superconducting layer can be formed from solid-state, or semi solid state, precursor materials deposited in the form of a dispersion. These precursor compositions allow for example the substantial elimination of $BaCO_3$ formation in final YBCO superconducting layers, while also allowing control of film nucleation and growth.

Two general approaches are presented for the formulation of precursor compositions. In one approach, the cationic constituents of the precursor composition are provided in components taking on a solid form, either as elements, or preferably, compounded with other elements. The precursor composition is provided in the form of ultrafine particles which are dispersed so that they can be coated onto and adhere onto the surface of a suitable substrate, intermediate-coated substrate, or buffer-coated substrate. These ultrafine particles can be created by aerosol spray, by evaporation or by similar techniques which can be controlled to provide the chemical compositions

and sizes desired. The ultrafine particles are less than about 500 nm, preferably less than about 250 nm, more preferably less than about 100 nm and even more preferably less than about 50 nm. In general, the particles are less than about 50% the thickness of the desired final film thickness, preferably less than about 30% most preferably less than about 10% of the thickness of the desired final film thickness. For example, the precursor composition can comprise ultrafine particles of one or more of the constituents of the superconducting layer in a substantially stoichiometric mixture, present in a carrier. This carrier comprises a solvent, a plasticizer, a binder, a dispersant, or a similar system known in the art, to form a dispersion of such particles. Each ultrafine particle can contain a substantially compositionally uniform, homogeneous mixture of such constituents. For example, each particle can contain BaF_2, and rare-earth oxide, and copper oxide or rare earth/barium/copper oxyfluoride in a substantially stoichiometric mixture. Analysis of such particles would desirably reveal a rare-earth:barium:copper ratio as substantially 1:2:3 in stoichiometry, with a fluorine:barium ratio of substantially 2:1 in stoichiometry. These particles can be either crystalline, or amorphous in form.

In a second approach, the precursor components can be prepared from elemental sources, or from a substantially stoichiometric compound comprising the desired constituents. For example, evaporation of a solid comprising a substantially stoichiometric compound of desired REBCO constituents (for example, $YBa_2Cu_3O_{7-x}$) or a number of solids, each containing a particular constituent of the desired final superconducting layer (for example, Y_2O_3, BaF_2, CuO) could be used to produce the ultrafine particles for production of the precursor compositions. Alternatively, spray drying or aerosolization of a metalorganic solution comprising a substantially stoichiometric mixture of desired REBCO constituents could be used to produce the ultrafine particles used in the precursor compositions. Alternatively, one or more of the cationic constituents can be provided in the precursor composition as a metalorganic salt or metalorganic compound, and can be present in solution. The metalorganic solution can act as a solvent, or carrier, for the other solid-state elements or compounds. According to this embodiment, dispersants and/or binders can be substantially eliminated from the precursor composition. For example, the precursor

composition can comprise ultrafine particles of rare-earth oxide and copper oxide in substantially a 1:3 stoichiometric ratio, along with a solublized barium-containing salt, for example, barium-trifluoroacetate dissolved in an organic solvent, such as methanol.

If the superconducting layer is of the REBCO type, the precursor composition can contain a rare earth element, barium, and copper in the form of their oxides; halides such as fluorides, chlorides, bromides and iodides; carboxylates and alcoholates, for example, acetates, including trihaloacetates such as trifluroracetates, formates, oxalates, lactates, oxyfluorides, propylates, citrates, and acetylacetonates, and, chlorates and nitrates. The precursor composition can include any combination of such elements (rare earth element, barium, and copper) in their various forms, which can convert to an intermediate containing a barium halide, plus rare earth oxyfluoride and copper(oxyfluoride) without a separate decomposition step or with a decomposition step that is substantially shorter than that which may be required for precursors in which all constituents are solubilized, and without substantial formation of $BaCO_3$, and which can subsequently be treated using high temperature reaction processes to yield an epitaxial REBCO film with T_c of no less than about 89K, and J_c greater than about 500,000 A/cm^2 at a film thickness of 1 micron or greater. For example, for a $YBa_2Cu_3O_{7-x}$ superconducting layer, the precursor composition could contain barium halide (for example, barium fluoride), yttrium oxide (for example, Y_2O_3), and copper oxide; or yttrium oxide, barium trifluoroacetate in a trifluoroacetate/methanol solution, and a mixture of copper oxide and copper trifluoroacetate in trifluoroacetate/methanol. Alternatively, the precursor composition could contain Ba-trifluoroacetate, Y_2O_3, and CuO. Alternatively, the precursor composition could contain barium trifluoroacetate and yttrium trifluoroacetate in methanol, and CuO. Alternatively, the precursor composition could contain BaF_2 and yttrium acetate and CuO. In some preferred embodiments, barium-containing particles are present as BaF_2 particles, or barium fluoroacetate. In some embodiments the precursor could be substantially a solublized metalorganic salt containing some or all of the cation constituents, provided at least a portion of one of the compounds

containing cation constituents present in solid form. In certain embodiments, the precursor in a dispersion includes a binder and/or a dispersant and/or solvent(s).

The precursor compositions can be applied to substrate or buffer-treated substrates by a number of methods, which are designed to produce coatings of substantially homogeneous thickness. For example, the precursor compositions can be applied using spin coating, slot coating, gravure coating, dip coating, tape casting, or spraying. The substrate is desirably uniformly coated to yield a superconducting film of from about 1 to 10 microns, preferably from about 1 to 5 microns, more preferably from about 2 to 4 microns.

More details are provided in commonly owned United States Patent Application Serial No. 09/500,717, filed on February 9, 2000, and entitled "Coated Conductor Thick Film Precursor".

In particular embodiments, methods can be employed to minimize the formation of undesirable a-axis oriented oxide layer grains, by inhibiting the formation of the oxide layer until the required reaction conditions are attained.

Conventional processes developed for decomposition and reaction of fluoride-containing precursors use a constant, and low, non-turbulent flow of process gas that is introduced into the decomposition furnace in an orientation that is parallel to the film surface, resulting in a stable boundary layer at the film/gas interface. In the apparatus types typically used for oxide layer precursor decomposition and reaction, the diffusion of gaseous reactants and products through this gas/film boundary layer appears to control the overall reaction rates. In thin, small area films (for example, less than about 0.4 microns thick and less than about a square centimeter), the diffusion of H_2O into the film and the diffusion of HF out of the film occur at rates such that the formation of the $YBa_2Cu_3O_{7-x}$ phase does not begin at any significant rate until the sample reaches the processing temperature. However, as the film thickness or area increases, the rates of gaseous diffusion into and out of the film decrease, all other parameters being equal. This results in longer reaction times and/or incomplete formation of the $YBa_2Cu_3O_{7-x}$ phase, resulting in reduced crystallographic texture, lower density, and reduced critical current density. Thus, the

overall rate of $YBa_2Cu_3O_{7-x}$ phase formation is determined, to a significant extent, by the diffusion of gases through the boundary layer at the film surface.

One approach to eliminating these boundary layers is to produce a turbulent flow at the film surface. Under such conditions, the local gas composition at the interface is maintained essentially the same as in the bulk gas (that is, the pH_2O is constant, and the pHF is approximately zero). Thus, the concentration of the gaseous products/reactants in the film is not controlled by the diffusion through the gas/film surface boundary layer condition, but rather by diffusion through the film. In order to minimize the nucleation of a-axis $YBa_2Cu_3O_{7-x}$ oriented grains on a substrate surface, the formation of the $YBa_2Cu_3O_{7-x}$ phase is inhibited until desired process conditions are reached. For example, the formation of the $YBa_2Cu_3O_{7-x}$ phase can be inhibited until desired process temperature is reached.

In one embodiment, a combination of: 1) low (non-turbulent) process gas flow, so that a stable boundary layer is established at the film/gas interface, during the ramp to temperature, and 2) high (turbulent) process gas flow, so that the boundary layer is disrupted at the film/gas interface, is employed. For example, in a three inch tube furnace, the flow can be from about 0.5 to about 2.0 L/min during the temperature ramp from ambient temperature to the desired process temperature. Thereafter, the flow can be increased to a value of from about 4 to about 15 L/min during the time at which the film is being processed. Thus, the rate of formation of $YBa_2Cu_3O_{7-x}$ and epitaxial texture formation can be increased at high temperature, while minimizing the amount of unwanted a-axis nucleation and growth at low temperature during ramp up. According to these processes, a-axis nucleated grains are desirably present in an amount of less than about 1%, as determined by scanning electron microscopy.

More details are provided in commonly owned U.S. Patent Application Serial No. _____, filed on even date herewith, and entitled "Control of Oxide Layer Reaction Rates".

In some embodiments, the invention uses two layers of biaxially textured HTS on a tape-shaped substrate. These embodiments are called "bilayered," while embodiments with more than two HTS layers are called "multilayered." Thus, the

layers are generally of the same width and length as the substrate, although HTS layers of somewhat narrower width and slightly shorter length could be used. In preferred embodiments the layers are stacked with respect to each other, although separated by one or more layers of non-conductive or highly resistive material.

Each HTS layer has a plurality of conductive path segments extending across the width of the layer, from one edge to another, and the path segments also have a component of direction along the length of the HTS layer. The path segments in the HTS layer surface are in electrically conductive communication with interlayer connections, which serve to allow current to flow from one HTS layer to another. Paths, which are made up of path segments, are periodically designed, so that current flow generally alternates between two HTS layers in bilayered embodiments, and traverses the layers through interlayer connections. Such an arrangement is shown in Fig. 4, which illustrates an example of a conductive path along and across HTS layers on a "basic" tape configuration. Referring to Fig. 4, a coated conductor 40 is shown, which includes substrate 42, a biaxially textured buffer layer 44, and epitaxial HTS layers 46 and 47, separated by non-conductive or highly resistive layer 49. Cap layer 48 has been removed for clarity. Conductive path 50 proceeds along path segment 52 across HTS layer 46, through interlayer connection 54 (shown as a dashed line), along path segment 58 (shown as a dashed line) across HTS layer 47 and through interlayer connection 60, to again proceed in HTS layer 46, along path segment 64, in the direction of net current flow (arrow 66). Although a single conductive path 50 is shown, it is understood that a number of paths are present in coated conductor 40, with their constituent path segments substantially parallel to the path segments and interlayer connections 52, 54, 58, 60, and 64 of conductive path 50, so that the plurality of conductive paths all have substantially similar shapes, in this case, flattened and right angled spiral shapes.

HTS layers can be constructed to contain a plurality of path segments which extend both across their widths and along their lengths. For example, HTS layers can be patterned so as to achieve a high resistivity or a fully insulating barrier between each of the plurality of path segments. For example, a regular periodic array of diagonal path segments can be imposed on the layer along the full length of the tape.

Patterning of HTS layers to give such arrays can be accomplished by a variety of means known to those skilled in the art, including for example, laser scribing, mechanical cutting, implantation, localized chemical treatment through a mask, and other known methods. After the patterning procedure, there are no low resistivity paths between individual path segments in the HTS layer surface. It will be readily apparent to those of skill in the art, that the various patterning means can each be used to create non-conductive or highly resistive regions between the conducting path segments. Each technique must eliminate or significantly reduce electrical contact between adjacent and nonadjacent path segments, to the full depth of the HTS layer. The resistance of these highly resistive regions must be such as to reduce the coupling losses to values below the target level, as based, for example, on formulas of Wilson and Kwasnitsa (referenced supra).

A patterned HTS layer according to a particular embodiment of the invention is shown in Fig. 5. Referring to Fig. 5, an epitaxially deposited HTS layer 70 is shown in an overhead view. An array of conductive path segments 72 extends diagonally across HTS layer 70. These path segments 72 are separated by non-conductive or highly resistive regions 74.

Suitable HTS layers which can be used to form conductive paths as described above can be fabricated in a variety of ways. They can be deposited, using the techniques described above, on both sides of a single substrate, buffered on both sides with biaxially textured buffer layers.

Alternatively, they can be fabricated one on top of the other on a single substrate, using techniques known to those skilled in the art, for example in making superconducting multilayers. This approach would require a technique for patterning the first HTS layer in such a way that the biaxially textured template is preserved for the subsequent layers; this can be achieved by an ion implantation or local chemical process (e.g. local deoxygenation) which alters the conductivity in narrow diagonal strips but leaves the underlying atomic structure unaltered.

Alternatively, and preferably, they can be fabricated, each on their own substrate and buffer, and then the two layers can be bonded together in a face-to-face configuration, as illustrated in Fig. 6. In a face-to-face configuration, exemplified in

Fig. 6, the two HTS layers may be coupled through a partially conductive intervening layer so that the effective thickness includes the thickness of the intervening layer. To minimize losses in this configuration with parallel a.c. field, it is necessary to keep the thickness of the intervening layer as small as possible, for example less than 10 microns, or in any case less than the critical hysteretic dimension for this orientation of field.

In some embodiments, multi-layer high temperature superconductors are provided, including first and second high temperature superconductor coated elements. Each element includes a substrate, at least one buffer layer deposited on the substrate, a high temperature superconductor layer, and optionally a cap layer. The first and second high temperature superconductor coated elements can be joined at the first and second cap layers, or can be joined with an intervening, preferably metallic, layer. Exemplary joining techniques include soldering and diffusion bonding.

Such a multi-layer architecture provides improved current sharing, lower hysteretic losses under alternating current conditions, enhanced electrical and thermal stability, and improved mechanical properties. Useful conductors can be made having multiple tapes stacked relative to one another and/or laminated to provide sufficient ampacity, dimensional stability, and mechanical strength. Such embodiments also provide a means for splicing coated tape segments and for termination of coated tape stackups or conductor elements.

Moreover, it is expected that this architecture can provide significant benefits for alternating current applications. AC losses are shown to be inversely proportional to the effective critical current density within the conductor, more specifically, the cross-sectional area within which the current is carried. For a multifilimentary conductor, this would be the area of the "bundle" of superconducting filaments, excluding any sheath material around that bundle. For a "face-to-face" architecture, the "bundle" critical current density would encompass only the high temperature superconductor films and the thickness of the cap layer structure. The cap layer can be formed of one or more layers, and preferably includes at least one noble metal layer. "Noble metal," as used herein, is a metal, the reaction products of which are thermodynamically unstable under the reaction conditions employed to prepare the

HTS tape. Exemplary noble metals include, for example, silver, gold, palladium, and platinum. Noble metals provide a low interfacial resistance between the HTS layer and the cap layer. In addition, the cap layer can include a second layer of normal metal (for example, copper or aluminum or alloys of normal metals). In direct current applications, additional face-to-face wires would be bundled or stacked to provide for the required ampacity and geometry for a given application.

Additionally, the high temperature superconductor film on the surface of the tapes could be treated to produce local breaks, that is, non-superconducting regions or stripes in the film only along the length of the tape (in the current flow direction). The cap layer deposited on the high temperature superconductor film would then serve to bridge the nonsuperconducting zones with a ductile normal metal region. An offset in the edge justification of the narrow strips or filaments, similar to a running bond brick pattern, would allow current to transfer to several narrow superconducting filaments both across the cap layers and to adjacent filaments, further increasing the redundancy and improving stability.

In all embodiments, a normal metal layer could be included along the edge of the conductor to hermetically seal the high temperature superconductor films and to provide for current transfer into the film, and if necessary, from the film into the substrate.

In particular embodiments, tensile strain on the superconducting layers can be minimized by providing the superconducting layer within a neutral mechanical axis zone. A "neutral mechanical axis" of a flexible material in the form of a tape of layered materials is a plane in the plane of the tape, coplanar with the layers of the tape, in which tensile strain experienced upon bending the material in a direction normal to the plane is zero. An operational layer centered on this axis will experience minimum tensile strain. A "neutral mechanical axis zone" is a region where the maximum strain experienced by the superconducting layer is less than that which would lead to degraded performance. The criterion for positioning the operational layer within the neutral mechanical axis zone is derived by balancing the moments in bending. This is done by properly specifying the thicknesses, positions, and Young's

modulus of the laminate layer or layers; laminate layers are those layers which are non-operational, and can include substrate, buffer and cap layers, for example.

More details are provided in commonly owned U.S. Provisional Patent Application Serial No. 60/145,468, filed on July 23, 1999, and entitled "Enhanced High Temperature Coated Superconductors," and commonly owned United States Patent Application Serial No. _____, filed concurrently herewith, and entitled "Enhanced High Temperature Coated Superconductors".

Referring to Fig. 6, a representative coated conductor 30 of this type is shown in a side view, including individual conductor elements 31a and 31b, with substrates 32a and 32b, biaxially textured buffer layers 34a and 34b, and epitaxial HTS layers 36a and 36b associated with conductor elements 31a and 31b, respectively. Cap layers 38a and 38b are similarly included. The individual conductors 31a and 31b are joined at the respective cap layers with interface 37 using one of a variety of methods, including soldering or gluing (e.g. epoxy), or by thermal or mechanical bonding, as known to those skilled in the art.

The face-to-face configuration can be modified and adapted as follows to achieve low a.c. loss for perpendicular, as well as for parallel a.c. magnetic field orientations. Each of the HTS layers are patterned, as shown in, for example, Fig. 7, and as described above. Further, the HTS layers are adapted to allow the conductive path segments in their surfaces to electrically communicate with conducting interlayer connections passing between the layers, at or near their edges. The interlayer connections will typically be normally conducting (not superconducting) but in special configurations could also be superconducting.

The interlayer connections can be fabricated in a variety of ways using techniques known to those skilled in the art. Normal (non-superconducting) metal interlayer connections can be established between HTS layers, for example using silver, gold, copper or high conductivity solders known in the art. In this case, the lengths of these interlayer connections are desirably as short as possible. Additionally, the widths of these interlayer connections are desirably chosen to make their cross-sectional areas desirably as large as possible, most desirably at least substantially equal to the cross-sectional areas of the diagonal filaments. Such

dimensions of interlayer connections can minimize the resistive losses associated with these nonsuperconducting path segments. These losses are desirably small compared to the desired maximum a.c. loss level for the given application.

Superconducting interlayer connections can be employed in cases where pedestals of superconducting material can be grown, for example, through via holes in an intervening non-conducting or highly resistive layer.

Interlayer connections provide electrical communication between HTS layers which are separated by non-conducting or highly resistive material which is positioned between the HTS layers. Such non-conducting or highly resistive material can be deposited on one HTS layer. Passages can be fabricated at the edges of the insulating material to allow the introduction of interlayer connections, followed by deposition of a further HTS layer.

In the simplest case, in the face-to-face configuration in which the HTS layers are patterned, a highly resistive layer 99 can be deposited over the central region of the tape, and silver 99 over the edges, as shown in Fig. 7a, and two of these tapes bonded face to face. Although the continuous silver connection at the edges can give rise to additional layers, in some cases this may be acceptable, and may simplify the fabrication.

One can also achieve a transposed configuration with HTS coated conductors by patterning an HTS layer into filaments parallel to the axis of the tape and winding the tape in a helical fashion around a cylindrical form. However, the smaller the cylindrical form is made to increase the packing density, the tighter the bending radius of the tapes, pushing them to the limits of their mechanical endurance.

The invention will be further described in the following examples, which do not limit the scope of the invention described in the claims.

EXAMPLES

The following examples illustrate properties and advantages of particular embodiments of the invention.

Example 1: Face-to-face Coated Conductor Configuration

A tape of biaxially textured nickel substrate coated with an epitaxial CeO2/YSZ/CeO2 buffer layer is coated with an epitaxial HTS YBCO film an epitaxial HTS YBCO film, as described in A. Malozemoff et al., Proceedings of Eucase Conference, Sitges, Spain, Sept. 14-17, 1999. Next the two long edges of the HTS layer are coated in a narrow contact zone (for example, about 5% of the overall width on each edge) with a non-superconductive, but highly conductive material, such as silver, compatible with the underlying YBCO film. The entire film is subsequently patterned via laser ablation, scribing or other processes to produce a regular pattern of diagonal YBCO strips forming conductive path segments, separated by an insulating or highly resistive gap. As shown in Fig. 5, the pattern in this particular example is chosen to be diagonal at an approximately 45 degree angle to the tape axis.

The conductive edge region is further processed by deposition of small areas (circular, rectangular or other shape) of contact material on top of the non-superconducting, highly conductive material along each edge. These contact material areas are placed so as not to bridge adjacent or nonadjacent conducting path segments. The contact material would typically be a compatible solder and potentially a flux, but could also include more silver. The contact pattern is developed such that it does not form a conductive path connecting conductive path segments in the pattern initially laid down on the film. Then an insulating or highly resistive layer is deposited over the exposed HTS material covering the main part of the strip. Alternatively, the exposed YBCO could be chemically treated to leave an insulating or highly resistive surface layer. This version of the HTS coated tape is shown in Fig. 7. Referring to Fig. 7, an overhead view of a coated conductor 80 is shown, including patterned HTS layer 81, conductive path segments 82, non-conductive or highly resistive regions 84, contact zones 86a and 86b, nonsuperconducting, highly conductive material 88, and contact material 90. An insulating or highly resistive layer can be placed between contact zones 86a and 86b, in a central channel of the layer. This layer has been removed for clarity, but is shown in the following Fig. 7a. An end view of the conductor is shown in Fig. 7a, showing substrate 92, buffer layer 94, HTS layer 96, non-superconducting, highly conductive material 98, and insulating layer 99.

Two tapes of material processed as above are then joined in a 'face to face' manner. That is, the coated faces are placed opposite each other so that the facing contact patterns join and form an electrical circuit. The edges are heated or otherwise reliably joined so as to promote the bonding of contact material at the contacts. The central insulating or highly resistive section can also be bonded together for mechanical integrity. This sandwich structure 100 is shown from overhead, and partially opened in Fig. 8. The topmost substrate and buffer layers are omitted for clarity. Like reference numerals indicate elements common to Fig. 7. The HTS films face each other (that is, they are not separated by substrate, but rather by cap material) and the outer surfaces of sandwich 100 consist of the substrate. The patterned strips form a series of 'zig zag' parallel conducting paths. Arrow 102 indicates current flow along a path segment from upper left to lower right in the topmost HTS layer, and dashed arrow 104 indicates current flow along a path segment from lower left to upper right in the lowermost HTS layer. As can be seen in Fig. 8, this example tape contains 19 separate conducting paths. The superconducting films are near the neutral mechanical axis of the composite sandwich when bent into or out of the plane of the paper.

Alternatively, the bonding between the two diagonally patterned HTS layers can be made by interposing an insulating film patterned with solder or silver dots at the edge, similar to movie film. This film is made of a suitable insulating material. Many such materials are known in the art, including those such as polyimide. The edges of the film are perforated and each perforation is filled with a conductive 'button,' made from, for example, solder or silver. This film can make it unnecessary to place contact material on the non-superconducting, highly conductive material in the contact zones shown in Fig. 7, and unnecessary to cover the HTS surface with an insulating or low conductivity layer. An example of this insulating layer is shown in Fig. 9. Referring to Fig. 9, insulating layer 110 is shown, including interlayer passages 112. This film is laid down on one of the pieces of prepared coated HTS tape; then the other piece of tape is laid over the top. The edges are heated or otherwise reliably joined so as to form a conducting joint and allow electrical communication from one face of the film to the other.

The following dimensions and parameters can be used to estimate power loss: 1) The full width of the tape is 4 mm. 2) The individual patterned diagonal YBCO segments are 0.3 mm wide and 2 microns thick. 3) The contact pads on the edges are circular, 0.2 mm in diameter and 2.5 microns thick for each layer. 4) The current density J_{fil} of the diagonal YBCO strips is 1 MA/cm^2 at the operating temperature of 77 degrees Kelvin. 5) The contact pads are silver and have a resistivity at operating temperature of 0.3 microOhm-cm.

Then the current of each individual filament is 6 A, and assuming for example that there are 14 independent filaments, the total dc critical current capacity of the tape is 84 A direct current (or 59 A rms). The root-mean-square (rms) loss per contact (total 5 microns thick) is 0.0085 mW, and the corresponding power loss per rms-amp per meter of tape length is 0.35 mW/Am. The local heat generated in the normal metal contacts is dissipated by close thermal contact with the surrounding material, to keep the local temperature at an acceptable level.

If an a.c. field of rms 0.1 T acts perpendicular to the plane of the tape, the hysteretic loss of the tape at a frequency of 50 Hz can be calculated using the Bean formula to be 0.43 mW/Am. This loss level, plus the resistive loss of the inserts, calculated above, gives a total of under 1 mW/Am, which is a reasonable design target for this perpendicular field level for applications like transformers.

Example 2: Fold-Over Configuration of Coated Conductor

In this example of the process, only one strip of HTS coated material is patterned with diagonal non-superconducting strips as shown in Fig. 10. Referring to Fig. 10, an overhead view of coated conductor 120 is shown, including top and bottom conductor elements, 122a and 122b, respectively. Each conductor element 122a or 122b includes patterned HTS layer 124a or 124b, inner contact zones 125a or 125b, and outer contact zones 126a or 126b, respectively. Each patterned HTS layer 124a or 124b includes conductive path segments 128a or 128b, and non-conductive or highly resistive regions 129a or 129b, respectively. Coated conductor 120 also includes bend line 130. An insulating or highly resistive layer can be placed between contact zones 125a and 126a, as well as between contact zones 125b and 126b, in

central channels of each conductor element. These layers have been removed for clarity, but are shown in the following Fig. 10a.

The substrate of the strip is scribed or formed on the side opposite the HTS layer in such a way as to promote folding of the strip lengthwise along the central axis without excessive 'bowing' or out-of-plane bending. This is done, for example, by forming a 'v' shaped groove in the surface of the tape. This is illustrated in Fig. 10a, an end view of coated conductor 120 shown in Fig. 10. Groove 132 is shown, and other reference numbers refer to elements previously described with respect to Fig. 7a and Fig. 10. In this example the tape is first patterned with two parallel strips of HTS material, separated by bend zone 134 disposed about bend line 130 in Fig. 10. Next the two HTS strips are patterned to yield diagonal-extending conductive path segments 128a and 128b, as shown in Fig. 10. After the HTS patterning step, contact zones 124a, 124b, 125a and 125b are formed on the strip. Each zone is formed at the edge of the HTS diagonal zones and occupies a small part of the total strip area (for example, about 5% at or near each edge). As in Example 1, the contact strips and HTS material are scribed or ablated or otherwise patterned to form separate diagonal non-conductive or highly resistive regions.

As in Example 1, above, the contact zones are prepared with non-superconducting, highly conductive material, suitable contact material applied (for example, flux or silver), and the surface of the superconductor coated with an insulator. Then the strip is folded lengthwise so as to bring the opposite edges and their contact dots together. The edges are then heated or otherwise reliably joined to bond the contacts and provide electrical communication between conducting elements 122a and 122b.

Alternatively, as in Example 1, the insulation function and contact material function may be carried out by introducing a separate insulating strip similar to movie film and the joint made as described above. With similar dimensions and material parameters as in Example 1, the a.c. loss of this resulting tape will be the same.

Example 3: Coated Conductor with Contact Tab

This example describes a method of making connections between the 'sandwich' and other conductors. This employs the insulating strip as in Examples 1 and 2. At the end it is patterned with silver, copper or other conductive material as shown in Fig. 11. Referring to Fig. 11, coated conductor 140 is shown, including elements previously referred to in Figs. 7 through 10. Additionally, conductive contact tab 142 is shown. Electrical communication is established between this tab and the conducting paths with leads 143, which terminate at interlayer connections 144. The pattern of electrical communication can be in the form of individual pathways as shown in Fig. 11, or an overall area of high-conductivity material. These patterns are arranged so as to make contact with the layer-to-layer joints formed by the opposing faces of the material. Tab 142 protrudes from the coated conductor. Alternatively, the conductors may be arranged on the outer edges of the sandwich or both patterns may be used. In either arrangement is it necessary to provide enough contacts to make connection to all the separate conduction paths in the sandwich. In addition, it is important that the normal resistance of the contacts or conductive area and conductors is as nearly equal as possible to promote sharing of current between the superconducting paths.

Example 4: Coated Conductor with Bridge Contacts

A problem that may occur in the sandwich of Examples 1 and 2 is that defects may be present in individual YBCO conductors. Due to the nature of the film there is little opportunity for current to be shunted out of the superconductor around these defects. The net result of a series of randomly placed defects would be severe degradation in performance of the sandwich. Fig. 12 shows a method of compensating for these defects. Referring to Fig. 12, highly resistive layer 150 is shown, including bridge contacts 146. Periodically 'bridge' contacts can be included in the inter-layer contact film. These bridge contacts interconnect all of the separate conductors so as to promote current sharing despite the presence of defects in one or more of the conduction paths. Evaluating the density of defects in the material and trading off the difficulty of reducing the defects in the material against the

degradation of a.c. losses allows one to determine the optimal number and spacing of these bridge sections. The bridge sections can be formed in the interposed film insulating layer or can be formed in the solder or silver pattern directly deposited on the conductive edge strips.

Example 5: Coated Conductor in a Double-Sided Configuration

Still another method of producing a transposed superconducting tape is to start with a substrate material perforated at the edge with a pattern of holes. The substrate is then further processed to deposit an HTS film on both sides. The holes are then filled with plugs of high-conductivity material shaped so as to make contact with both sides of the film. This may require the deposition of conductive strips on each edge of both sides of the material as in Example 1. Scribing, laser ablation or other means to produce a pattern of conductive strips alternating from one side of the strip to the other may then pattern the HTS strips. It would have a similar property to the above strips of having reduced a.c. losses when compared to a non-patterned strip. With hole dimensions as in Example 1, silver as the plug material and a thickness of 25 microns, the resistive loss due to the silver plugs would be 1.75 mW/Am.

It is to be understood that while the invention has been described in conjunction with the detailed description thereof, the forgoing description is intended to illustrate and not limit the scope of the invention, which is defined by the scope of the appended claims. Other aspects, advantages, and modifications are within the scope of the following claims.

What is claimed is:

1. A coated conductor comprising a plurality of multilayered conductive paths, wherein each conductive path comprises:

at least a first and a second high temperature superconducting layer; and

a plurality of interlayer connections between said layers,

wherein at least one of said layers is deposited epitaxially on an a biaxially textured buffer-coated substrate surface.

2. The conductor of claim 1, wherein said conductive paths are bilayered.

3. The conductor of claim 1, wherein said substrate material is in the form of a tape having length and width.

4. The conductor of claim 1, wherein said conductive path has a maximum width, wherein said width is less than the critical hysteretic dimension.

5. The conductor of claim 1, wherein both the first and second conducting layers comprise high temperature superconductor material deposited epitaxially on buffer-coated substrate surfaces.

6. The conductor of claim 1, further comprising a cap layer deposited on at least one of said conducting layers.

7. The conductor of claim 5, wherein said first and second conducting layers are deposited epitaxially on opposing surfaces of a biaxially textured buffer-coated substrate.

8. The conductor of claim 5, wherein each of said first and second conducting layers are deposited epitaxially on surfaces of first and second biaxially textured buffer-coated substrates.

9. The conductor of claim 8, wherein each of said first and second conducting layers further comprise first and second highly resistive layers deposited on said conducting layers.

10. The conductor of claim 9, wherein said first and second highly resistive layers are joined.

11. The conductor of claim 1, wherein said conductive paths comprise path segments extending along said first conducting HTS layer, extending through at least one interlayer connection from said first conducting layer to said second conducting HTS layer, extending along said second conducting layer, and extending through at least one interlayer connection from said second conducting layer to said first conducting layer.

12. The conductor of claim 11, wherein said interlayer connection is a normal metal.

13. The conductor of claim 12, wherein said interlayer connection is silver, copper, gold or a high conductivity solder.

14. The conductor of claim 11, wherein said interlayer connection is a high temperature superconductor.

15. The conductor of claim 11, wherein said path segments have directional components along the length and width of each layer, and wherein said path extends across the entire width of each layer.

16. The conductor of claim 15, wherein said path segments are substantially straight.

17. The conductor of claim 16, wherein said path segments are substantially parallel.

18. The conductor of claim 11, further comprising a highly resistive layer positioned between said first and said second conducting HTS layers.

19. The conductor of claim 18, wherein said interlayer connections pass through said highly resistive layer.

20. The conductor of claim 11, further comprising a contact tab in electrical communication with substantially all conducting paths.

21. The conductor of claim 11, wherein groups of conducting paths are in electrical communication by providing common conducting path segments.

22. A method of making a coated conductor, said method comprising:

a) providing at least two high temperature superconducting layers, wherein at least one of said layers is epitaxially deposited on buffer-coated substrate surface, and wherein each layer comprises a plurality of conductive path segments extending along and across the surfaces of said layers; and

b) providing a plurality of interlayer connections adapted to individually correspond to each of said conductive path segments,

wherein said conductive path segments and said interlayer connections together form a conductive path which extends along said coated conductor.

23. The method of claim 22, wherein said first and second conducting layers are deposited epitaxially on opposing surfaces of a biaxially textured buffer-coated substrate.

24. The method of claim 22, wherein each of said first and second conducting layers are deposited epitaxially on surfaces of first and second biaxially textured buffer-coated substrates.

25. The method of claim 24, further comprising the step of applying at least one highly resistive layer to at least one of said conducting layers.

26. The method of claim 25, wherein said conducting layers are joined, with said highly resistive layer interposed between said conducting layers.

27. The method of claim 25, further comprising bonding said highly restive layers together to form said conductive path.

28. The method of claim 22, wherein said first and second conducting layers are deposited epitaxially on the same side of a single substrate, with an intervening high resistivity layer between said conducting layers, and said interlayer connections established through or around said intervening high resistivity layer.

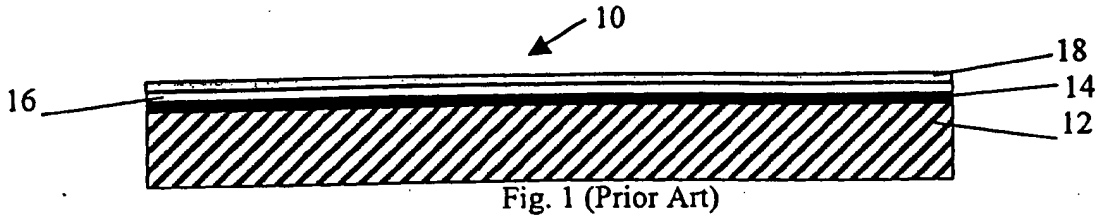


Fig. 1 (Prior Art)

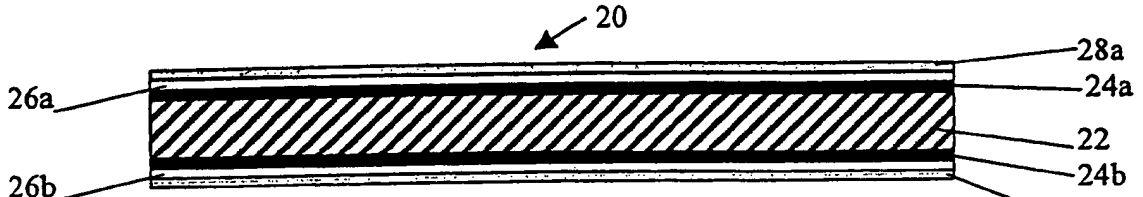


Fig. 2 (Prior Art)

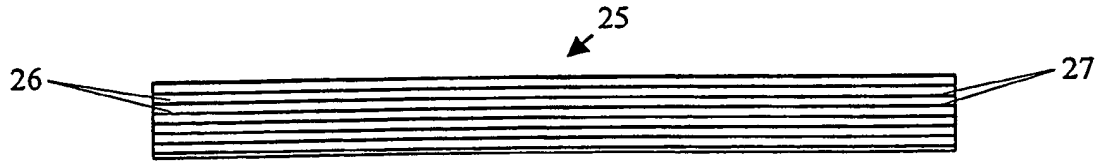


Fig. 3 (Prior Art)

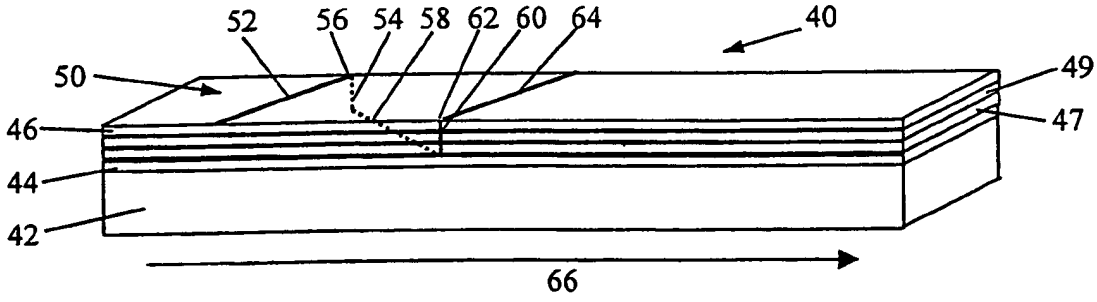


Fig. 4

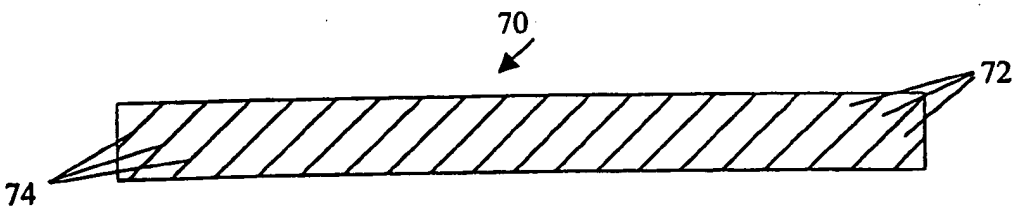


Fig. 5

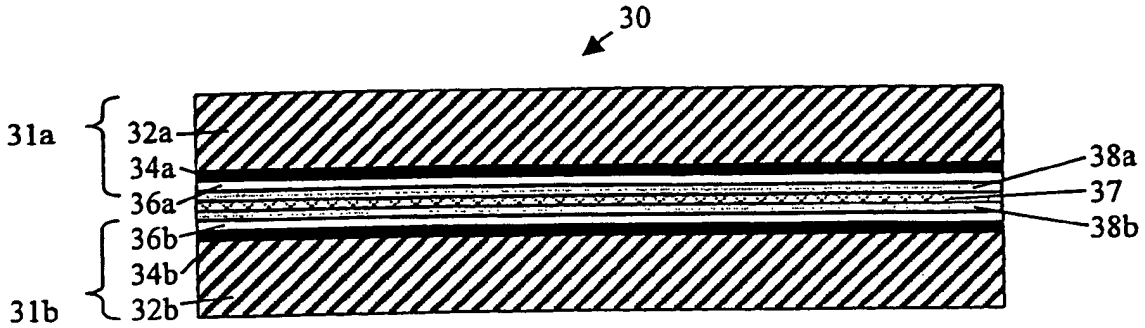


Fig. 6

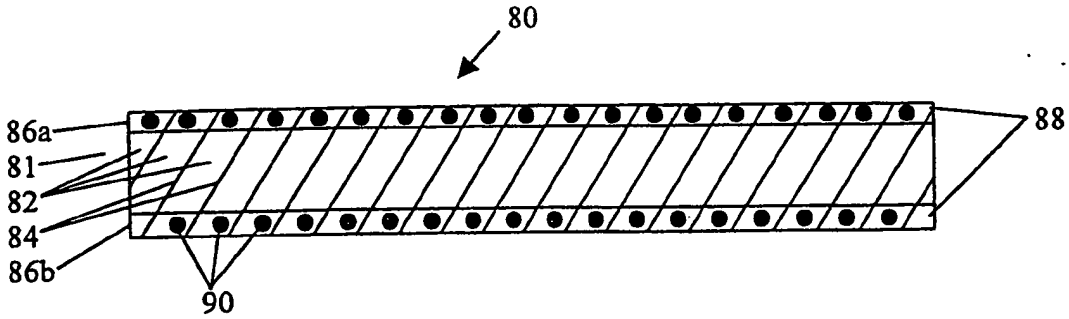


Fig. 7

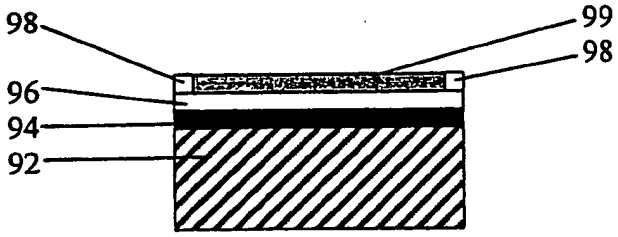


Fig. 7a

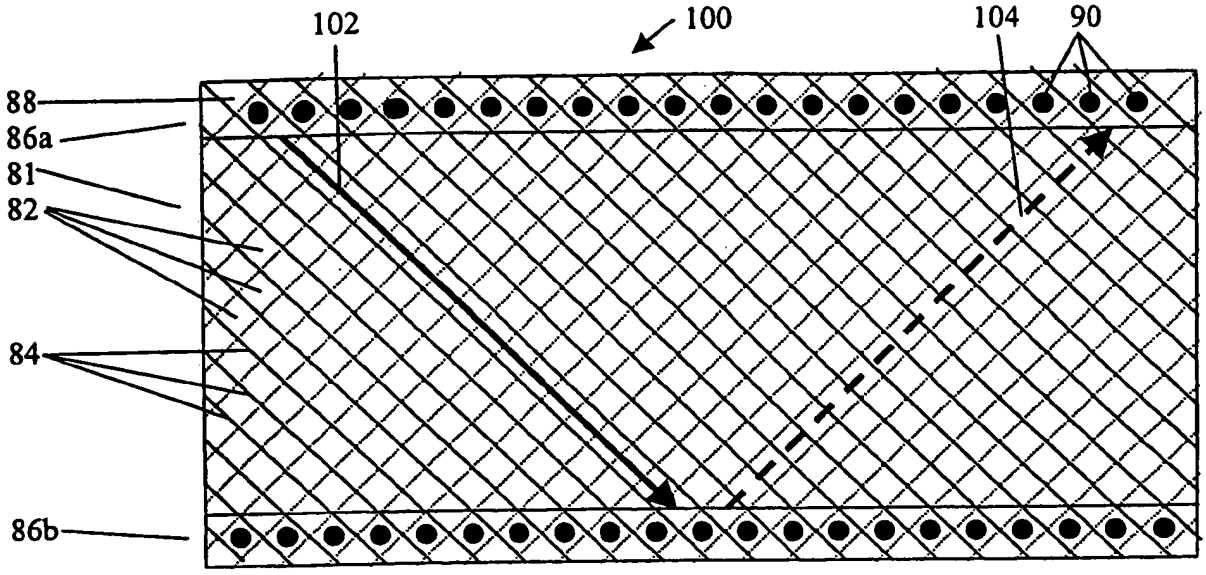


Fig. 8

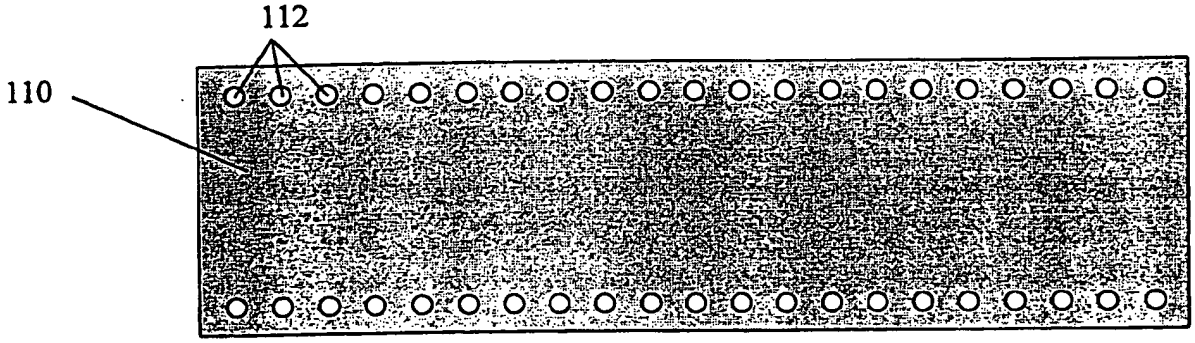


Fig. 9

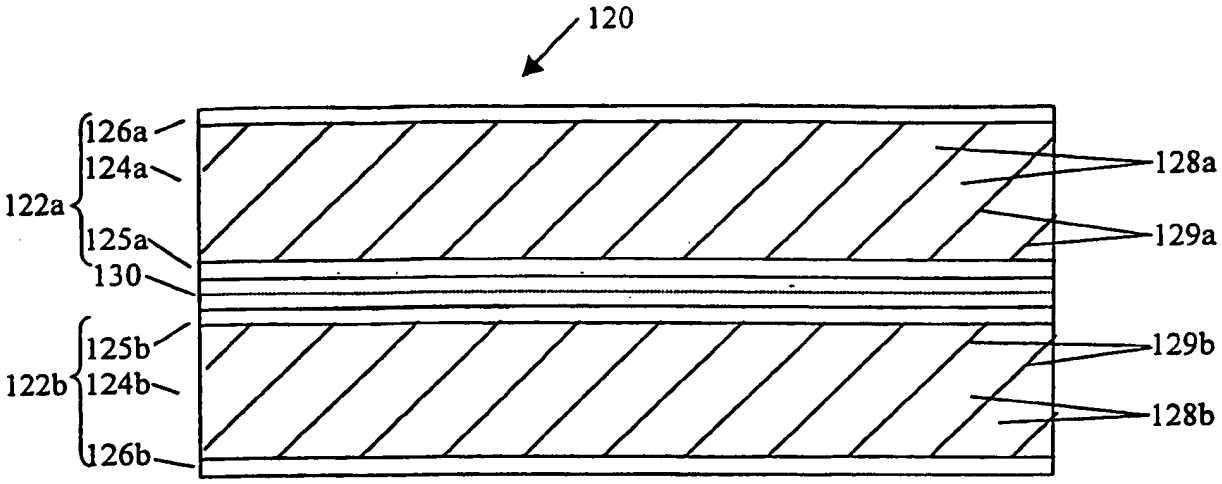


Fig. 10

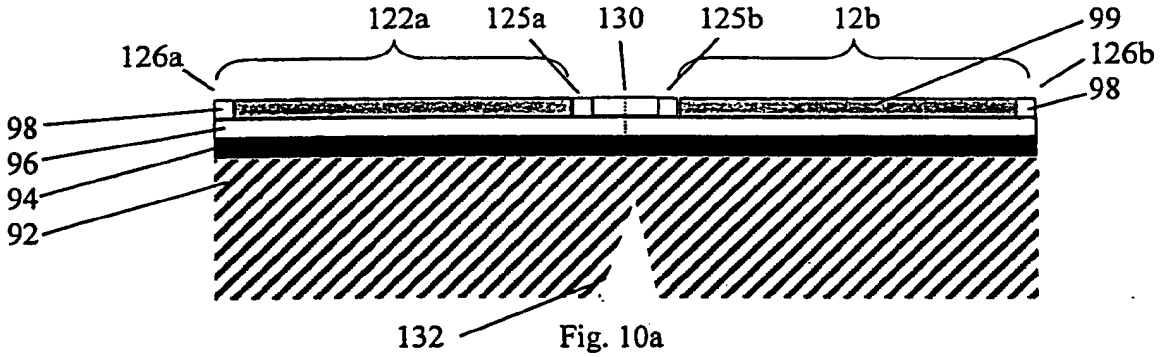


Fig. 10a

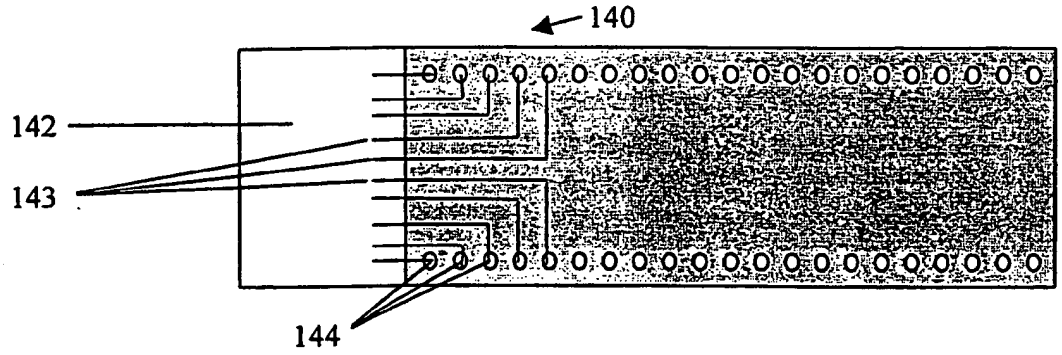


Fig. 11

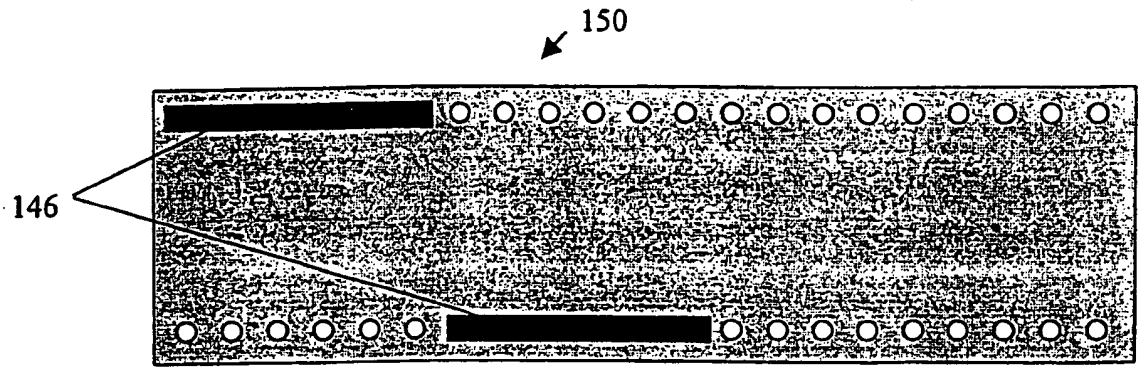


Fig. 12